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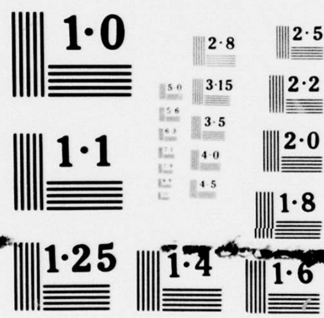

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TECHNICAL REPORT TE-77-4

OPTICAL ROLL REFERENCE

Advanced Sensors Directorate
Technology Laboratory

1 April 1977

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US Army Missile Research and Development Command
Redstone Arsenal, Alabama 35809

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20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

This report documents several alternative approaches to the implementation of polarized-light roll references that have been investigated over the last two years. Atmospheric amplitude modulation effects are discussed; means for eliminating these effects are found.

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I. REQUIREMENTS

A. Need for Vertical Reference

Several existing Army missile systems presently employ vertical gyroscopes on board the missile to provide an indication of "up" which is necessary for missile guidance. An optical roll-reference is simply an alternative to this on-board gyro. In cases where environmental difficulties exist with the gyro (such as severe launch shocks), it may provide a particularly suitable alternative. In cases where an optical communication link already exists, it may be easy to implement without major impact on that optical link. In addition, the cost and reliability may well be improved over a vertical gyro.

B. Application

1. Command-to-Line-of-Sight (CLOS)

Present CLOS systems require this vertical reference either to stabilize the missile roll or to convert guidance commands (transmitted relative to launch station coordinates) to the missile coordinate system on a rolling missile. Future CLOS systems, such as the optical beamrider, could readily use an optical reference, because the optical communication link would already exist.

2. Growler

Growler is a candidate for replacement of artillery on a cost and mobility basis. It is simply a "free" rocket with command guidance during the early portion of the flight to correct for large launch dispersion. The knowledge at the launch site of rocket roll angle during flight would greatly simplify the on-board guidance equipment. An optical roll reference utilizing a retroreflector on the rocket is a natural for this application.

3. High "G" Launch

Some systems, such as the Armaments Command (ARMCOM) ballistic beamrider, employ a launch (up to 50,000 G) which presently prohibits use of an operating gyro. Success of this system depends on development of an alternate roll reference such as this optical reference.

C. Modes of Operation

From the preceding discussion, it is apparent that several different modes of operation may be employed. Table I shows various combinations of rolling or roll stabilized missiles and information requirements (on missile or at launch station) to meet the various applications.

TABLE 1. MODES OF OPERATION

Missile	Information	
	On Missile	At Launcher
Rolling	CLOS, Beamrider Guided Projectile	CLOS, Growler
Roll Stabilized	CLOS, Beamrider	CLOS

II. APPROACH - POLARIZED LIGHT

A. Basic Function

If linearly polarized light is passed through a polarizer, the output intensity is proportional to $\cos^2 \theta$, where θ is the angle between the polarizer polarization and input beam polarization. If the polarizer is a beamsplitting prism such as a Glan Thompson or Wollaston, the two outputs are perpendicularly polarized, with intensities proportional to $\cos^2 \theta$ and $\sin^2 \theta$. If this polarizer (often called analyzer when used to sense angle of polarization) is on board a missile, the missile rotation relative to the polarization of an optical beam may then be directly measured.

B. Atmospheric Effects

Theoretical analysis* indicates that the atmosphere should rotate the plane of polarization approximately 10^{-9} rad/km. Experiments seem to validate this small effect. Thus the roll angle resolution of a polarized optical roll reference should be quite small.

However, if a real time measurement is to be made of $\cos^2 \theta$ (or $\sin^2 \theta$) to determine θ accurately, it is seen that atmospheric amplitude modulation effects do influence the received signal level and thus indirectly cause noise in the determination of the roll angle θ. This could be described as $A(t) \cos^2 \theta$, where $A(t)$ is the atmospheric amplitude modulation as a function of time. Clearly accurate measurements of θ must account for this amplitude modulation. Several alternatives exist:

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*"An Investigation of Laser Wave Depolarization Due to Atmospheric Transmission," IEEE Journal of Quantum Electronics, Volume QE 3, No. 11, November 1967.

1. Narrow Band Filtering

If the roll rate to be measured is sufficiently constant, many measurements of θ may be made and averaged. If this averaging time is longer than the atmospheric modulation frequencies, the resolution will be improved.

2. Normalization

Both $\sin^2 \theta$ and $\cos^2 \theta$ are available if a beam-splitting prism is used. It noted that $\sin^2 \theta + \cos^2 \theta = 1$ is a trigonometric identity which simply means in this case that the total output of the beamsplitter is equal to its input (with some constant transmission loss). However, this sum output is modulated in the same manner as $\cos^2 \theta$ by the atmospheric scintillation. Therefore, if the desired signal is divided by this sum signal, the atmospheric modulation, A(t), is removed. Thus:

$$[A(t) \sin^2 \theta]/[A(t) \sin^2 \theta + A(t) \cos^2 \theta] = \sin^2 \theta \quad .$$

Angular accuracy then depends on how well this normalization may be performed. One simple way is to use logarithmic amplifiers and then subtract the outputs. It is also obvious that the following could be used:

$$A(t) \sin^2 \theta / A(t) \cos^2 \theta = \tan^2 \theta \quad .$$

This form is particularly useful if log amplifiers are used to obtain the required division, because the sum is not required. The $\pm$ infinity of $\ln \tan^2 \theta$ may be of little consequence if provision is made (log amplifiers merely limit at these angles.)

Figure 1 shows waveforms of the various waveforms discussed, but without the atmospheric pertubations.

C. Two θ Ambiguity

It is easily seen from Figure 1 that a 180° ambiguity exists in determining θ from $\sin^2 \theta$ or $\cos^2 \theta$. This is also apparent from the trigonometric identities:

$$\sin^2 \theta = 1/2\ (1 - \cos 2\theta)$$

$$\cos^2 \theta = 1/2\ (1 + \cos 2\theta) \quad .$$

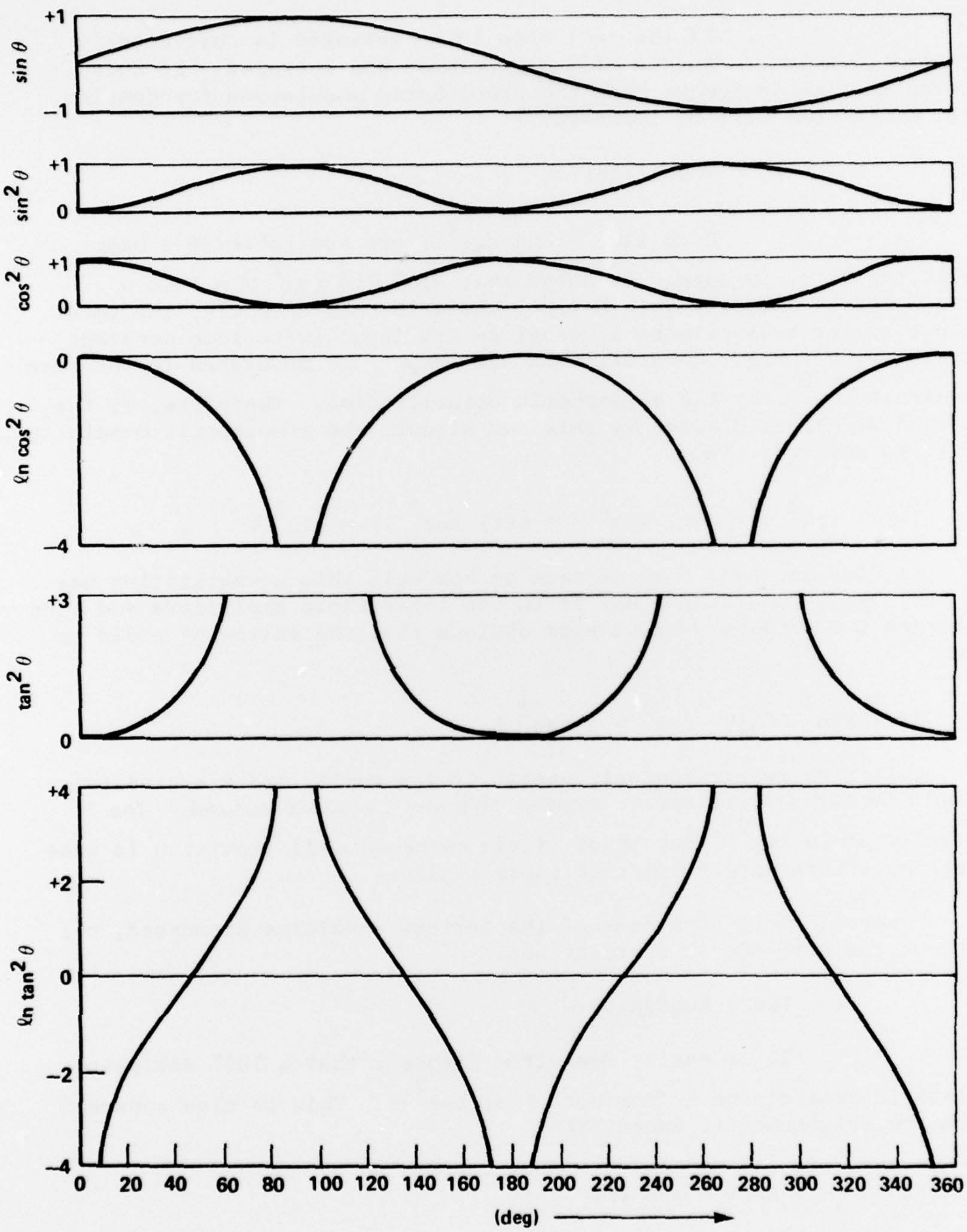


Figure 1. Roll reference waveforms.

This ambiguity is inherent in the polarizer/analyser process itself; resolution requires some additional mechanization. However, if the 180° ambiguity is solved at one point in time (immediately after launch for example), the proper phasing may be retained for the remainder of the missile flight if the missile does not reverse roll direction.

Many approaches to this ambiguity resolution are being examined. Some examples are: earth electrostatic field sensors, sky (brightness) sensors, ground sensors such as GaAs proximity fuses, control (or prediction) of roll angle within 180° during launch, or optical angle measurements using known launch geometry. The last three techniques are the most promising due to their simplicity. However, this report is concerned with processing of the roll angle information, assuming one of these techniques has been used immediately after launch and the 2θ ambiguity solved.

III. LABORATORY TESTS

One very simple and obvious test is a verification of the waveforms of Figure 1 using commercially available Polaroid film. No anomalies were noted. However, a problem arises in the ground-based information mode where a retroreflective prism on the missile returns the optical signal to the launch site for processing. Due to the nature of the retroreflector, a polarization rotation results. Further, the six different return beams (identified by the order in which they strike the three retroreflector mirrors) may be rotated differently. A simple laboratory experiment using a polarized laser, retroreflector, Polaroid film, and optical detector produced the results shown in Table 2. Receiver polarization is indicated parallel or perpendicular to beam polarization.

It was obvious that a polarized film should be placed over the retroreflector for the ground-information mode of operation. When this is done, the transmitted beam should be unpolarized. The other possibility of polarized beam and unpolarized receiver suffers from the non-availability of atmospheric normalization.

IV. FIELD TESTS

A. Hardware

The transmitter used was a Spectra Physics Model 120 polarized HeNe laser, with a dc power of approximately 4 mW, and beam divergence of 1.0 mrad. The receiver consisted of a 2.0-in. diameter f/1 fresnel lens, a partially silvered glass beamsplitter, and two PIN 10 detectors covered with Polaroid film. The two films were oriented 90° to one another, and 45° to the transmitter beam. Preamplifiers were Signetics 747 operational amplifiers used in an inverting voltage gain

TABLE 2. RESULTS OF POLARIZATION ROTATION

Beam	Receiver	Retro	Effects
Unpolarized	Polarized	Polarized	100% Modulation, 2θ
Polarized	Unpolarized	Polarized	100%, 2θ
Polarized	Polarized Parallel	Unpolarized	Low Modulation, 4θ*
Polarized	Polarized Perpendicular	Unpolarized	Low Signal, Low Modulation, 4θ*
Polarized	Polarized Parallel	Polarized	100%, 2θ
Polarized	Polarized Perpendicular	Polarized	100%, 4θ

*Effect is dependent on angle between retro axis and beam axis, may be 6θ or more, and is never high level high modulation.

mode. Test were also run using a Coherent Associates Model 20 acusto optic modulator to square wave modulate the laser at 1 kHz.

B. Test Results

All tests were conducted over relatively level grassy terrain with a mean beam height approximately 2 m above the ground.

1. Narrow Band Filter

The first test employed only the unnormalized $\sin^2\theta$ detector output and a narrow bandpass filter. The retroreflector with polarizer was rotated at 13 Hz, producing a 26-Hz amplitude modulation. The narrow band filter consisted of an operational amplifier with a twin-tee filter (at 26 Hz) in the feedback. Filter Q was spoiled to a value of approximately 50. At 1.0-km range, the filter output indicated signal present; however, instrumentation to measure phase relative to the retro angle was not available. Although this test showed communication existed, the narrow Q would not be a practical solution due to variation of missile roll rate during flight.

2. Phase Lock Loop

A phase lock loop was next designed which would serve as a narrow filter, but permit slow frequency changes during flight. Test were similar to those of the twin-tee tests, except that a radio link was used to provide retro rotation angle for phase comparisons. Locking of the phase lock loop was achieved; however, break lock

usually occurred in less than 60 sec indicating a low signal-to-noise (S/N) ratio due to atmospheric amplitude modulation, so the normalization approach was attempted.

3. Normalized Receiver

The receiver electronics were then modified to provide $(\ln \sin^2 \theta) - \ln (\sin^2 \theta + \cos^2 \theta)$. The transmitter was modified to permit amplitude modulation at 1 kHz, and a one-way communication (receiver downrange looking into the transmitter beam) set up. This test operated very well at the 1-km range.

The circuitry was again modified to provide $\ln \sin^2 \theta - \ln \cos^2 \theta$, which simplifies the electronics by permitting the preamps themselves to be logarithmic. This circuit functioned equally well at 1.0 km, so additional range was attempted. Angular resolution of approximately 5° was obtained at 5-km range.

The test setup using the rotating retroreflector/polarizing film was then conducted using this $\ln \tan^2 \theta$ electronics. Good angular measurement was limited to approximately 500 m. Investigation showed the polarizing film over the retroreflector decollimated the return beam, significantly reducing signal level. It is not yet known to what extent this decollimating effect is inherent in higher quality polarizing films.

V. TYPICAL CIRCUIT DESIGN

A. Rolling Missile

Figure 2 shows a block diagram of an optical roll reference system that should work very well for the missile borne information mode. Adaptation to the ground-information mode will require more transmitter power unless low dispersion films can be found.

The design utilizes $\sin^2 \theta$ and $\cos^2 \theta$ with logarithmic amplifiers to produce $\ln \tan^2 \theta$. The $\ln \tan^2 \theta$ waveform is shown in Figure 3, with the clipping performed by the log amps shown.

The phase lock loop could reproduce $\sin^2 \theta$ (or $\cos^2 \theta$), but as shown provides real time parallel output binary digital roll angle, θ. This function is provided as follows. The voltage controlled oscillator (VCO) frequency is N times the 2θ frequency input. State of the N flip flops in the $\div$N counter provides N bit resolution on 2θ. The separate $\div 2$ provides resolution of the 180° ambiguity, once set (or read) to the external ambiguity resolving mechanism.

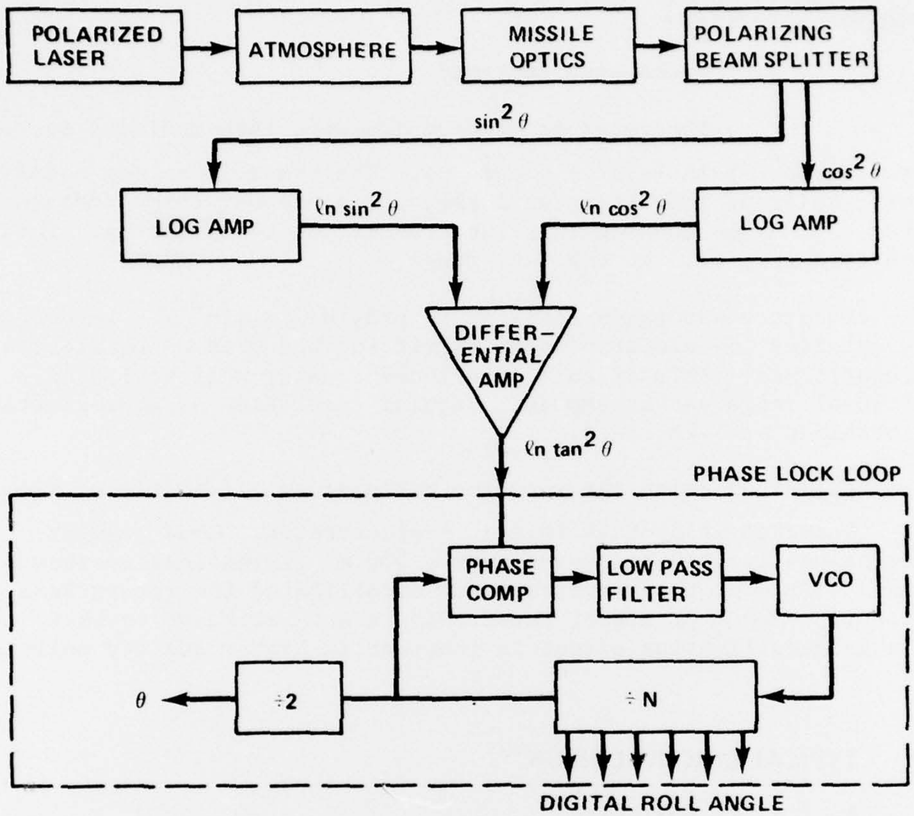


Figure 2. Typical circuit design, rolling missile.

An alternative approach would be to replace the phase locked loop of Figure 2 with an analog-to-digital (A/D) converter, and program a prom to provide θ output with $\ln \tan^2 \theta$ input.

B. Typical Circuit Design, Roll Stabilized Missile

It is noted from Figure 3 that the $\ln \tan^2 \theta$ waveform provided by the circuit of Figure 2 is monotonically increasing from $\theta = 0$ to $\theta = \pi/2$, with a value of zero at $\theta = \pi/4$. Thus $\ln \tan^2 \theta$ is a usable measure of θ over this range for input to a servo control loop to maintain the missile roll angel at $\theta = \pi/4$.

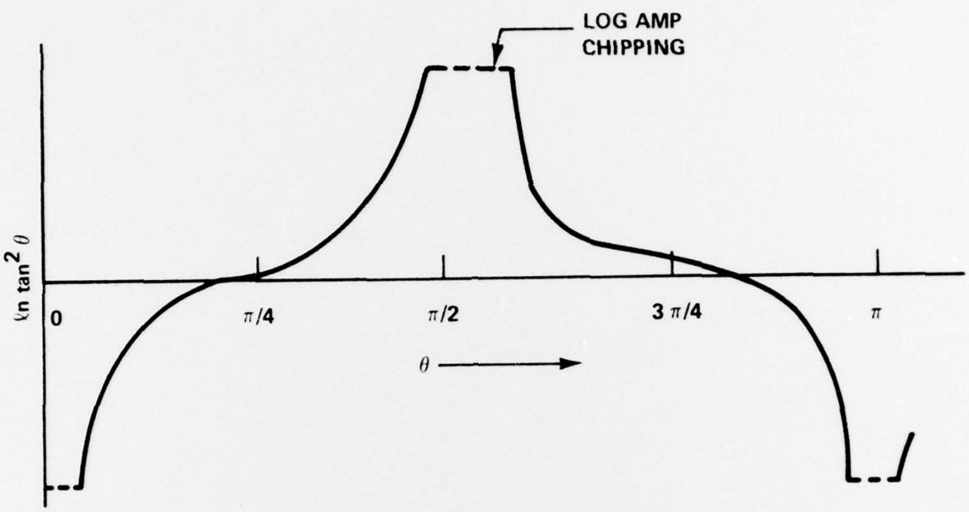


Figure 3. $\ln \tan^2 \theta$.

VI. CONCLUSIONS

The following conclusion were made:

a) Test data were limited by signal level and hardware angular resolution, not by atmosphere.

b) One-way transmission was far easier than the retro due to polaroid film decollimation effects.

c) Either normalized implementation performs the angle measuring function satisfactorily.

Appendix. TEST HARDWARE DESCRIPTION

1. Twin-Tee

Figure A-1 shows the schematic of the twin-tee filter used in this experiment. Figure A-2 shows the filter response as a function of the spoiling resistor, Rs. The 505 value was selected for a bandwidth slightly less than 1 Hz.

2. Phase Lock Loop

Figure A-3 shows the schematic of the phase lock loop filter The extremely heavy filtering of the VCO input resulted in an effective bandwidth somewhat less than that of the previously mentioned twin-tee filter.

3. Atmospheric Normalization

Two circuits were implemented. One provided $\ln \sin^2 \theta - \ln (\sin^2 \theta + \cos^2 \theta)$; the other provided $\ln \sin^2 \theta - \ln \cos^2 \theta$. The log amplifier used in these tests is given in Figure A-4. It provides a low load impedance to the detector and eight orders of magnitude dynamic range with an upper frequency cut-off of approximately 8 kHz.

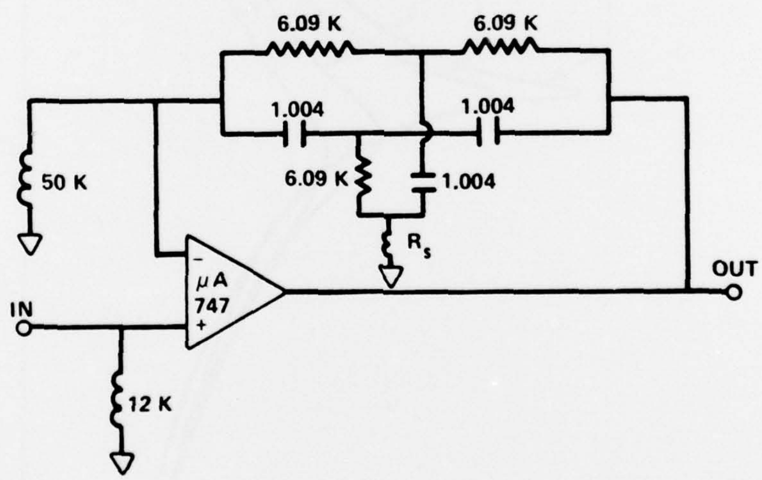


Figure A-1. Twin-tee filter.

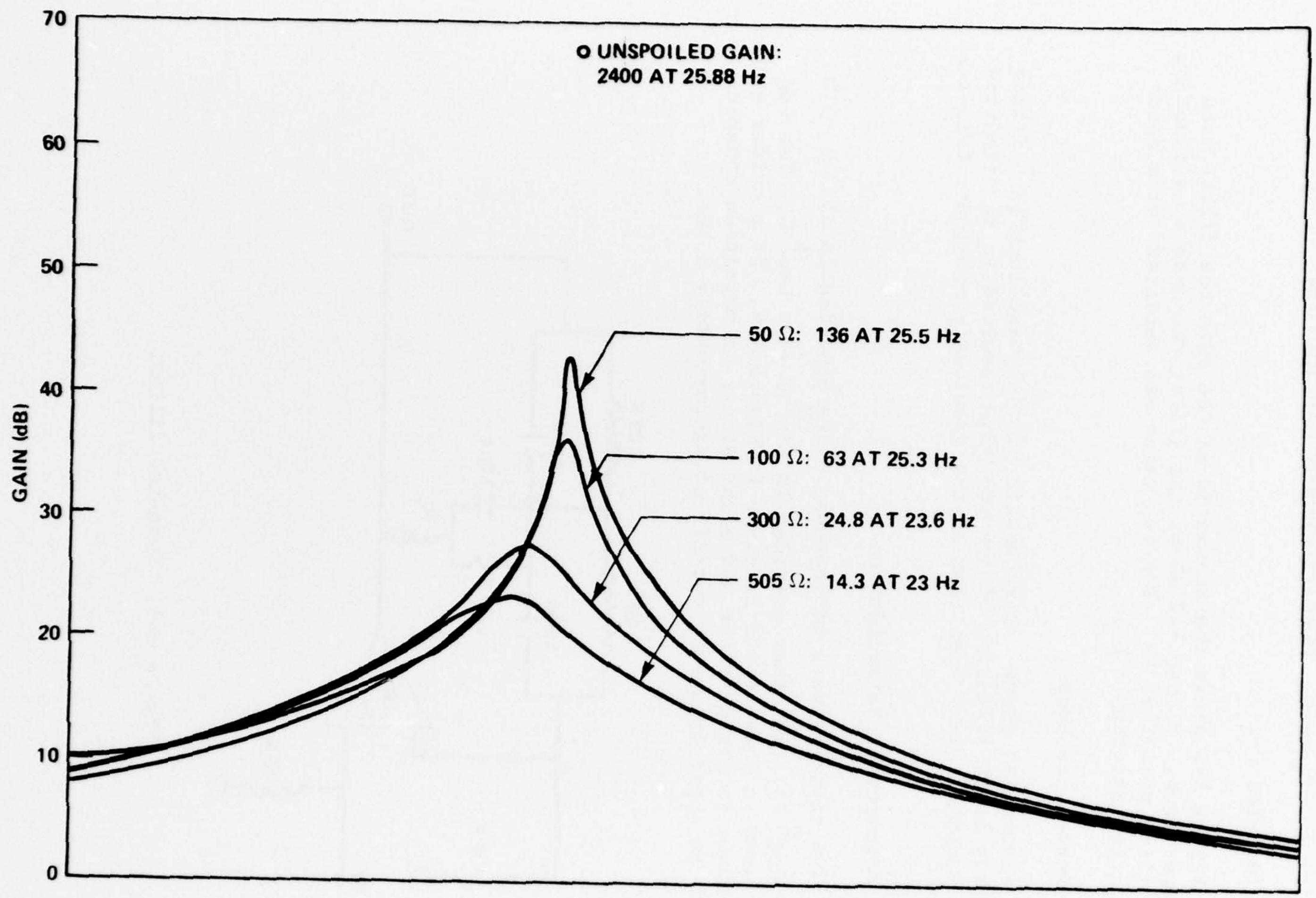
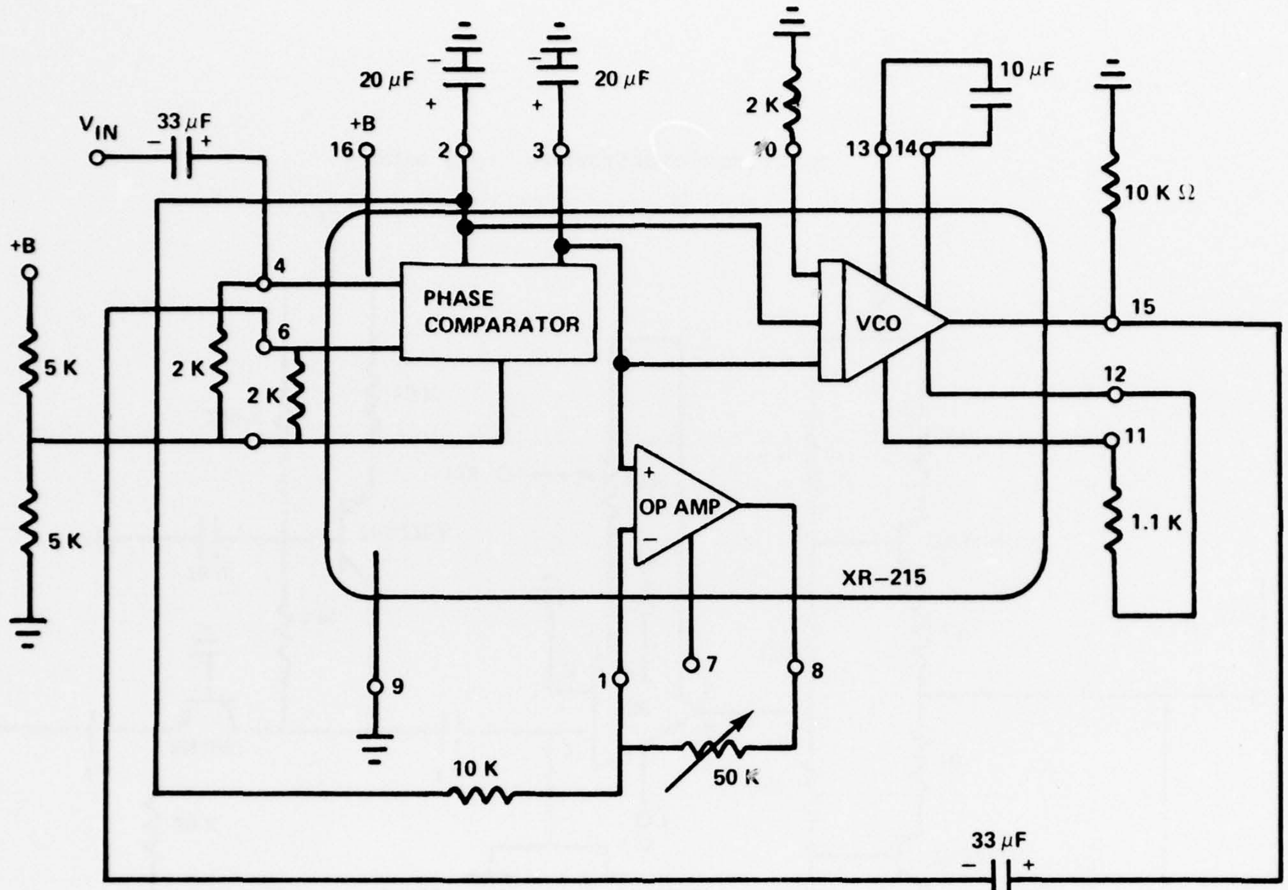


Figure A-2. Filter response.



f_o OF VCO = 26 Hz

$\Delta W_{CAPTURE} = 2\pi$ (5 Hz) = 31.5

$\Delta W_{LOCK} = 2\pi$ (20 Hz) = 125.7

Figure A-3. Phase lock loop.

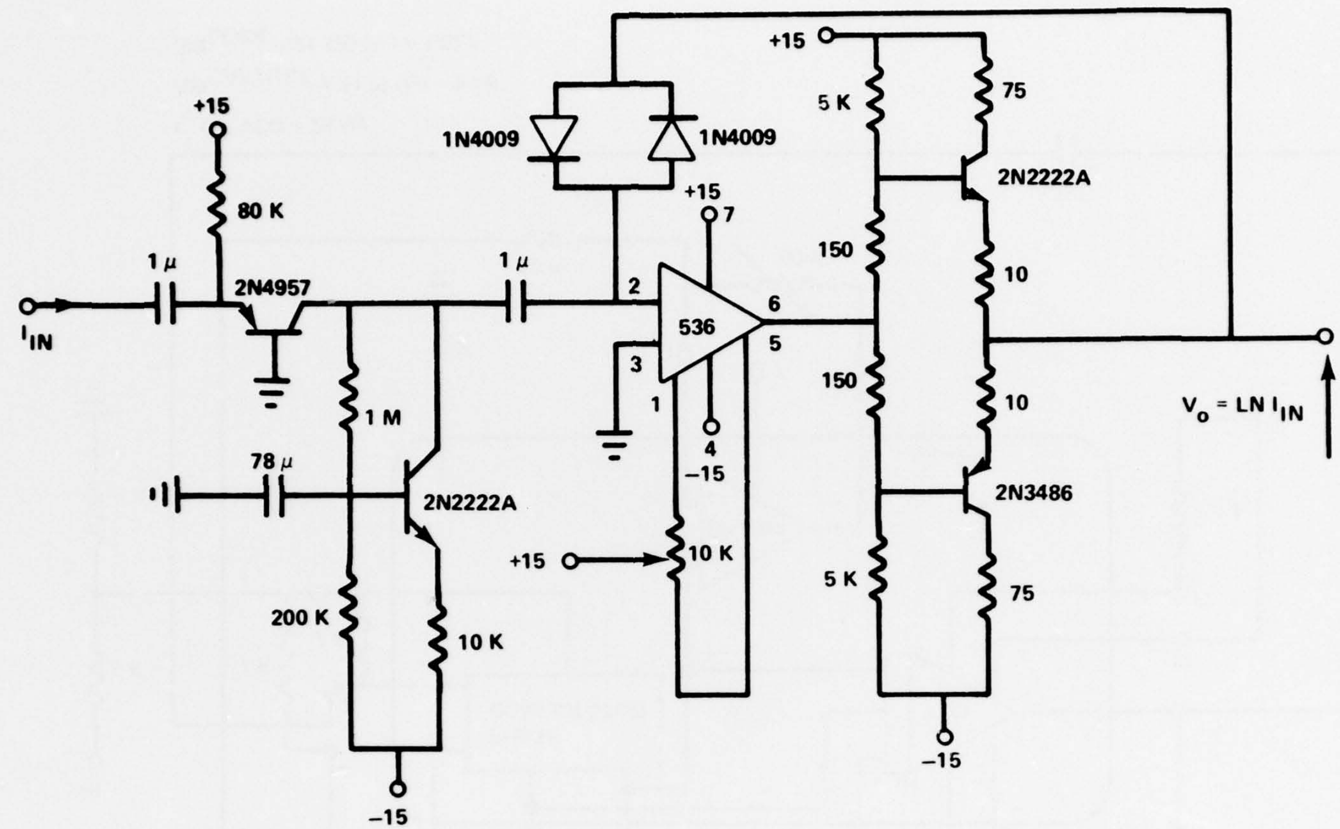


Figure A-4. Logarithmic amplifier.

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